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MAGNETIC FIELDS OF ACTIVE GALAXY NUCLEI AND COSMOLOGICAL MODELS

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Abstract

We present the review of various methods of detection of magnetic field strengths in the nearest regions of the active galaxy nuclei (AGN) which are the high energetic machines. Original spectropolarimetric method developed in the Pulkovo Observatory is based on the effect of polarization plane rotation on the mean free path respect to electron scattering in the plasma. In a result the spectrum of polarized radiation depends essentially on radiation frequency unlike the classical case of Thomson scattering. This fact allows us to determine the magnitude and geometry of the magnetic field in the region of the optical and more hard electromagnetic radiation. The results of theoretical calculations are compared to the results of spectropolarimetric observations of AGN. The extrapolation of estimated magnitudes of magnetic fields to the nearest region of supermassive black holes (SMBH) allows us to determine the magnetic fields of SMBHs. We developed the method of determining magnetic fields through the spectrum synchrotron radiation in the region of synchrotron self-absorption. As the magnitude of magnetic field of the extragalactic source depends very strongly on the angular size of extragalactic source and therefore on the photometric distance the calculated magnetic field magnitudes depends very strongly on the definite cosmological model. This result allows us to present the new method for determination of the most important cosmological parameters including dark matter and dark energy parameters.

1 Introduction

Magnetic fields are responsible for many aspects of plasma inflow and outflow in active galactic nuclei (AGNs). Magnetic fields provide outward angular momentum transport in the accretion process via magnetorotational instability, with accompanied dissipative heating that allows further mass-inflow. Strong poloidal magnetic fields are thought to thread centrifugal winds, which could carry away angular momentum, while confining and collimating large-scale outflows and jets seen in many AGNs. The existence of broad-line region in AGNs may be provided namely by magnetic pressure. Fig.1 shows a remarkable variety of structure of typical AGN nearest region including accretion disk, disk corona, wind stream lines, etc.

First part of our paper is including the short description of new method of determination of magnetic fields developed in the Pulkovo Observatory. The main idea of this method is taking into account the Faraday rotation of the polarization plane in the mean free path of electron (Thomson) scattering. In a result a nontrivial wavelength dependence of polarization arises when the Faraday rotation angle ψ at the Thomson depth τ (see Gnedin and Silant'ev 1997)

$$\psi = 0.4 \left(\frac{\lambda}{1\mu m}\right)^2 \left(\frac{B}{1G}\right) \tau \cos\theta \tag{1}$$

is sufficiently large. Here, λ is the radiation wavelength and θ is the angle between the line of sight and magnetic field B. We present the results of calculations of polarized radiation of the accretion disk and accretion outflow near a supermassive black hole which is thought to be in the centre of AGNs.

The text of this paper is also including the brief review of results of polarimetric observations of AGNs and QSOs. The basic new our idea is to use the future precise measurements of magnetic fields of AGNs

and QSOs for investigating of various cosmological models and especially for determination of the equation of state (EOS) of dark energy. The main method for solving this problem is determination of magnetic field of extragalactic radio structures using their synchrotron spectra in the region of synchrotron self-absorption. In this case the magnetic field magnitude depends very strongly on the value of photometric distance. The last one depends in this turn on the real cosmological model. It appears that the magnetic field strength of the given source can be different in many times for various cosmological models. Thus we are obtaining the new method that allows us to make the decisive choice between numerous cosmological models. We expect that this method could have more advantage over the modern classical SNe and WMAP methods.

2 The basic results of polarimetric observations of AGNs

Fig.2 presents the results of spectropolarimetric observations of the sample of extragalactic targets chosen by Cabanac et al. (2005) from Veron-Cetti and Veron (2000) and the Sloan Digital Sky Survey. The targets included the bright extragalactic sources having higher probability to show stronger polarization: BAL quasars and red quasars. The selection criteria of the sample were detailed by Hutsemekers et al. 2001,2005. To avoid possible contaminations from the interstellar medium of the Galaxy only the objects at galactic latitude $b_{gal} > 30$ grad were selected. Above this galactic latitude the interstellar polarization is smaller. This sample spans the redshift range $0 < z < 3$ homogeneously. Fig.2 shows the dependence of the quasar sample polarization on redshift. Overall the quasar polarization degrees do not correlate with redshift though the slight enhancement of highly polarized quasars at lower redshift seems to be real. Fig.2 (right panel) presents the histograms of the linear polarization degree of the quasar sample (black line) and of the star sample selected over the same region (grey line) are superimposed. Both panels are used from Cabanac et al. (2005). The star polarization histogram shows much smaller polarization degrees to that which corresponds to minor contamination from the interstellar polarization. Decreasing the number of polarized quasars with increasing polarization degree may be interpreted as the effect of depolarization due to magnetic Faraday effect.

Hutsemekers and Lamy, 2001, and Hutsemekers et al. 2005 discovered coherent orientations of quasar polarization vectors on cosmological scales. It appears that quasar polarization vectors are not randomly oriented over the sky with a probability often excess of 99.9%. The polarization vectors appear coherently oriented or aligned over huge (~ 1 Gpc) regions of the sky located at both low ($z \sim 0.5$) and high ($z \sim 1.5$) redshifts and characterized by different preferred directions of the quasar polarization (Fig.3). The left panel shows a map of the polarization vectors. The right panel shows the logarithmic significance level of the coherent orientation for the sample of 213 polarized quasars. Hutsemekers et al.(2005) claimed existence a regular alternance along the line of sight of regions of randomly and aligned polarization vectors with typical commoving length scale of 1.5 Gpc. Furthermore, the mean polarization angle seems to rotate with redshift at the rate of $\sim 30^\circ$ per Gpc. They excluded the effect of contamination by interstellar polarization in our Galaxy. Though it is not possible to exclude the intrinsic quasar origin of this alignment, the other possibility is that both the polarization vector alignments and the rotation of the mean polarization angles are due to a physical mechanism which affects the light on its travel on the line of sight. Such mechanism was considered by Gnedin 1994 and by Gnedin and Krasnikov 1992 and it consists in photon-pseudoscalar mixing within a magnetic field. Mixing process produces light polarization in an external magnetic field. The coupling between electromagnetic and pseudoscalar fields affects the polarization properties of the electromagnetic waves as they propagate through a magnetic field. The value of linear polarization due to magnetic conversion of photons into pseudoscalar bosons is derived by the expression:

$$P_l = A \sin^2 (\frac{1}{2} g_{\alpha\gamma} B_\perp l) \qquad (2)$$

where $B_\perp = B \sin\theta$ is the perpendicular component of a magnetic field, θ is the angle between the photon propagation and magnetic field directions, l is the characteristic dimension of a magnetic field, $g_{\alpha\gamma}$ is the photon-pseudoscalar coupling constant. The alignment effect requires existence of regular magnetic field on the cosmological scales ~ 1 Gpc with the magnetic field strength at the level of $\sim 1 \div 10$ nG. There is now evidence of existence of such huge magnetic fields on cosmological scales (Blasi and Olinto, 1999, Dar and De Rujula, 2005). This evidence was obtained via observations of Faraday rotation of light from distant QSOs.

3 Measurement of the spectrum of linear polarized radiation from magnetosphere of compact object - a new method to determine the magnetic field

The existing magnetic field of the astrophysical object is the additional factor in optical anisotropy of a surrounding this object plasma. The radiation of such object acquires linear polarization as a result of scattering on electrons. The scattered radiation undergoes Faraday rotation by propagation in magnetized plasma. The angle of Faraday rotation ψ is determined by the expression (1). The integral linear polarization of light occurs even for a spherically symmetric density distribution of electrons if the magnetic field has no axial symmetry coinciding with the line of sight. Fig.4 demonstrates action of this effect. The radiation only scattered in equatorial volumes is polarized because Faraday rotation angle is negligible for radiation direction across magnetic force lines.

Another important effect is the polarization of radiation scattered from an accretion disk that also undergoes to Faraday rotation and Faraday depolarization. Photons escape the optically thick disk basically from the surface layer with $\tau \sim 1$. If the Faraday rotation angle corresponding to this optical length becomes greater than unity, then the emerging radiation will be depolarized as a result of the summarizing radiation fluxes with different angles of Faraday's rotation. Only for directions that are perpendicular to the vertical magnetic field the Faraday rotation angle is too small to yield depolarization effect. Certainly, the diffusion of radiation in the inner part depolarizes it even without magnetic field because of multiple scattering of photons. The Faraday rotation only increases the depolarization process. It means that the polarization of outgoing radiation acquires the peak-like angular dependence with its maximum for the direction perpendicular to magnetic field. The sharpness of the peak increases with increasing magnetic field strength. The main region of allowed angles appears to be $\sim 1/\delta$, where the parameter depolarization:

$$\delta = 0.8 \left(\frac{\lambda}{1\mu m}\right)^2 \left(\frac{B}{1G}\right) \tag{3}$$

Fig.5 shows the dependence of the polarization degree of outgoing radiation from magnetized optically thick plasma disk. The maximum value of polarization is equal to 9.14% instead of the classical value 11.7% corresponding to multiple electron scattering without magnetic field. The results of our calculations (see Gnedin et al.2005) polarization for the various models of optically thick accretion disk with vertically averaged magnetic field are presented by the Table 1.

AGNs and QSOs are characterized with strong outflows from accretion disks. Punsly (2001) developed the theory that a wind of magnetized plasma from the nearest vicinity of supermassive black hole can be driven by the interaction of the black hole gravitational field and a plasma filled magnetosphere. He investigated the fundamental process that allows a rotating black hole to power a magnetized wind. The basic Punsly's idea is that the poloidal magnetic field is generated in the region between the inner radius of the accretion disk and the horizon (ergosphere). Our basic idea is that cooperative action of the wind outflow and rotation of a black hole can transfer the poloidal magnetic field in the magnetic field of Parker type:

$$B_r = B\left(\frac{R_S}{r}\right)^2 \cos\theta$$

$$B_\varphi = B\frac{ka}{M}\frac{1}{1-a/M}\left(\frac{R_S}{r}\right)\cos\theta\sin\theta \equiv C\left(\frac{R_S}{r}\right)\cos\theta\sin\theta$$

$$B_\theta = 0 \tag{4}$$

Here B is the polar magnetic field at the inner radius R_S of the accretion outflow, θ is the angle between the dipole axis and the radius-vector, a/M is the well-known dimensionless black hole angular momentum parameter, k is the specific physical parameter ~ 1 of a black hole ergosphere. The results of our calculation of polarization are presented at Fig.6. This Fig. reveals that if the toroidal component is much less that and radial one the scattered radiation is nearby depolarized. With increasing toroidal component, i.e. with reaching the value $a/M \sim 1$ the polarization spectrum removes in more hard wavelength region, the width of spectral dependence being narrow. In principle, the increase of the radial component makes also shift of the maximum polarization into hard energy, but in this case much

Table 1: Degree of polarization for the various models of an accretion disk with vertically averaged magnetic field.

Model	$B_{eq}(R)$	$P_l(\lambda)$
Accretion disk with ion supported flows	$\sim R^{-5/4}$	$\sim \lambda^{-1/3}$
Sunayev-Shakura disk (a) $P_r \gg P_g$	$\sim R^{-3/4}$	$\sim \lambda^{-1}$
Sunayev-Shakura disk (b) $P_g \gg P_r$	$\sim R^{-9/8}$	$\sim \lambda^{-1/2}$
Sunayev-Shakura disk (c) $P_g \gg P_r$	$\sim R^{-21/16}$	$\sim \lambda^{-1/4}$
Hot accretion disk with plasma viscosity	$\sim R^{-15/28}$	$\sim \lambda^{-9/7}$
Payne-Eardley disk $P = P_g$, $\alpha = 1$	$\sim R^{-21/8}$	$\sim \lambda^{-1/8}$
Magnetic accretion-jet ejection disk without equipartition	$\sim R^{-5/2}$	$\sim \lambda^{4/3}$
Accretion disk with non-zero torque on inner edge	$\sim R^{-15/16}$	$\sim \lambda^{-1}$
Disk with reprocessing	$\sim R^{-7/4}$	$\sim \lambda^{-1/8}$

more stronger magnetic field strength is required. The real conclusion is that more faster rotating black holes will have higher level polarization compared to slowly rotating black holes. It means that the level of polarization and its spectral distribution is acceptable test for distinguishing between Kerr and Schwarzschild black holes.

The plasma outflow from the magnetosphere and the inner part of the accretion disk gives rise to an envelope. The radiation scattered in the envelope acquires the linear polarization. The region of the formation of broad emission lines observed in AGNs is a case of such envelope. In the absence of magnetic field the scattered radiation has to be non -polarized provided the scattering matter in the spherically shape envelope is symmetric relative to the line of sight. If the magnetic field is not symmetric relative to this line, the outgoing radiation (singly or multiply scattered) has to undergo influence of the Faraday's rotation effect and become to be polarized. The integral polarization of radiation is equal to zero if the dipole magnetic moment M is coaxial with the line of sight or in the case of $B = 0$. The results of numerical calculations of polarization are presented in Fig.7 as function of dimensionless parameter δ, where $B = M/a^3$ is the dipole magnetic field on the surface of radiation source. This parameter changes from 0 up to 100. The peak value of the polarization occurs when M is perpendicular to the line of sight.

4 Magnetic fields of the extragalactic radio sources: exploration of the cosmological models

We demonstrate the principal possibility to explore the various cosmological models through measurements of the magnetic field magnitudes of the compact radio galaxies. The magnetic field strengths of the compact extragalactic radio structures can be estimated from the synchrotron spectra of radio sources if one takes into account the synchrotron self-absorption process. In this case the most important physical value is the observed synchrotron self-absorption frequency ν_p at that the optical thickness respect to the synchrotron self-absorption becomes equal to unite. Then the expression for the magnetic field strength B is determined by Slysh,1963, and Hirotani, 2005:

$$B = 10^{-5} b(\alpha) \left(\frac{\nu_p}{1GHz}\right)^5 \left(\frac{\theta}{mas}\right)^4 \left(\frac{1Jy}{S_p}\right)^2 \frac{\delta}{1+z} \tag{5}$$

Here S_p is the flux density at the frequency ν_p, δ is the boosting factor, the coefficient $b(\alpha)$ depends on the index of synchrotron radiation. Its value lies in the region $b = 2 \div 3$ for the wide range of values α.

This formula was successively used by Artukh and Chernikov, 2001, Tyul'bashev and Chernikov, 2001, for determination of magnetic fields of concrete extragalactic radio sources.

Our main idea is to use this formula for exploration various cosmological models using in this formula the well-known expression for angular diameter θ of the radio source:

$$\theta = \frac{l(1+z)^2}{D_L(z)} \tag{6}$$

where D_L is, so-called, the photometric distance. This distance depends on the real cosmological model. For the commonly accepted the dark matter (DM) and dark energy (DE) model the expression for the photometric distance takes the form:

$$D_L(z) = \frac{c}{H_0}(1+z)\int_0^z \frac{dx}{H(x)/H_0} \tag{7}$$

Where the Hubble parameter is:

$$H(z) = H_0\left[\Omega_m(1+z)^3 + \Omega_\Lambda f(z)\right]^{1/2} \tag{8}$$

Ω_m and Ω_Λ are the ratios of the modern total matter density and dark energy density to the critical density, correspondingly, and what is more $\Omega_m + \Omega_\Lambda = 1$. The function $f(z)$ depends on the equation of state of dark energy $p(z) = w(z)\rho(z)$:

$$f(z) = \exp\left[3\int_0^z \frac{1+W(z)}{1+z}dz\right] \tag{9}$$

One can see that the magnitude of magnetic field depends very strongly on the photometric distance and therefore on the real cosmological model. The relation (9) means also that the value magnetic field in the radio luminosity region depends essentially on the form of the equation state of dark energy. Such dependence appears to be more strongly that it looks in the classical methods of SNIa and cosmic microwave background anisotropy (WMAP).

We demonstrate the power of this method on the example of the sample of the Gigahertzs Peaked Spectrum sources (GPS) that presents the class of intrinsically compact objects (linear size at parsec scale). This sample defined on the basis of their spectral properties (see Tinti et al., 2004): the overall shape is convex with turnover frequencies of a few GHz and the spectrum at high frequencies is steep. The best fitting physical mechanism is the synchrotron emission of the relativistic electrons with the synchrotron self-absorption (SSA).

The key problem is the determination of the photometric distance which is really dependent on the basic parameters DM and DE. We are considering the some examples of the cosmological models when $\Omega_m + \Omega_\Lambda = 1$ and $P_{DE} = W\rho_{DE}$, where $W >< 0$ for different cosmological models and then:

$$H(z) = H_0\left[\Omega_m(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+W)}\right]^{1/2} \tag{10}$$

For popular LCDM (Lambda-Cold Dark Matter) model it follows $W = -1$, for model with noninteracting cosmic strings $W = -1/3$. In the Universe with domain walls the DE equation of state requires $W = -2/3$. At last, in the so-called phantom model it appears that $W < -1$. Our calculations of the Eq.(5) show that the magnitude of the magnetic field of one definite radio source can differ at 2 - 3 times for various cosmological models mentioned here.

We present in the Table 2 the results of calculations of magnetic fields of the GPS source ($z = 3.626$) for various cosmological models. The names of the models presented in this Table are: LA corresponds to the following expression for DE coefficient $W(z) = W_0 + W_1 z/(1+z)$ and $W_0 = -1.40$, $W_1 = 1.66$ (Linder, 2003). Linear means $W(z) = W_0 + W_1 z$ with the same values of W's. P2 is a quadratic polynomial of $H(z)$ (Alam et al.,2004). P3 is a cubic polynomial $H(z)$. CA is the generalized cardassian cosmology (Freese, 2005). Quiess means the DE with constant equation of state W. MCG is a modified form (Chimento et al. 2004) of the Chaplygin gas (Fabris et al. 2001). Brane 2 means brane world cosmology (Sahni and Shtanov, 2003, Sahni and Alam, 2002).

One can see that there is a real difference in magnitudes of magnetic fields for various cosmological models. It means that measurements of magnetic fields of active galaxy nuclei and quasars allow us to choose the real cosmological model from numerous theoretical models of evolution of our Universe.

Table 2: Magnetic field strengths for GPS source 1424+2256 (z = 3.626) in various cosmological models.

Model	**B(mG)**
LA (3)	0.152
P2 (4)	0.129
Linear (5)	0.245
CA (7)	0.034
Quiess (8)	0.079
MCG (9)	0.085
Brane 2 (10)	0.083
LCDM	0.080

The basic difference between the cosmological models can be formulated by the following way. Magnetic fields of AGNs in the phantom cosmological model with $W < -1$ is less than in the cosmological models with $W \geq -1$, i.e. $B(W < -1) < B(W = -1)$. We reveal the following relation between magnitudes of magnetic fields for GPS 1424+2256 ($z = 3$) for Standard Cold Matter (SCDM) and commonly accepted LCDM models:

$$B_{SCDM}/B_{LCDM} = 7 \tag{11}$$

Magnetic field is greater for brane world model and Chaplygin gas model compare to classical LCDM model. For curvature theory of gravity the magnetic field also is strongly greater than for LCDM model, and what is more B_{curv}/B_{LCDM} can reach ~ 100. Our calculations show also that magnetic fields for the same source in positive curvature universe and in negative curvature universe can differ each from other, at least, two times.

It is interesting to consider the situation with dynamical behavior of dark energy. There is an evidence to show that the dark energy might evolve from $W > -1$ in the past to $W < -1$ today and cross $W = -1$ in the intermediate redshift (see, for example, Huang and Guo, 2005). The basic question is what explicit value of transition redshift. There is some evidence from SNIa, that transition from decelerating to accelerating takes place at $z \sim 0.6$, but Huang and Guo, 2005, found that this transition takes at $z \sim 1.7$. We calculate the magnetic field strength for the radio source GPS 1424+2256 ($z = 3.626$) with and without transition from decelerating to accelerating. If the transition takes at $z \sim 0.6$, the ratio $B_{tr}/B_{LCDM} = 5.4$. If the transition takes place at $z = 1.7$ then $B_{tr}/B_{LCDM} = 2.7$. This result means that it is possible to distinguish two various transitions: $z \sim 0.6$ and $z \sim 1.7$ via measurements of magnetic field. For $z = 3.626$ the ratio $B(0.6)/B(1.7) = 2.27$. Thus the future measurements of magnetic fields of active galaxy nuclei and quasars will be able make decisive contribution to solution of the problem of evolution of the Universe. In the Table 3 the results of calculations of magnetic field strength for the number of the GPS sources are presented for the cosmological models with different deceleration parameter q_0. The scaling linear dimension of radio region l_0 is chosen as $l_0 = 2$ pc. Our results allows to determine the magnitude of magnetic field in the close vicinity of the supermassive black hole horizon. If one suggests the conservation of the magnetic flux one can estimate this magnitude. The data of the Table 3 show that this magnitude can reach the value $B_H \sim 10^8 \div 10^9$G at the horizon of a supermassive black hole.

5 Conclusions

The alignment of the polarization vectors of AGNs and QSOs discovered by Hutsemekers and their colleagues may be explained as the effect of conversion of photons into pseudoscalar bosons in the intergalactic magnetic field. Polarimetric observations in optical range and radio spectral observations of AGNs and QSOs allow us to measure the magnetic field magnitudes. It is interesting that the magnetic field strength determined from radio spectrum in the model of synchrotron self-absorption mechanism appears to be strongly dependent on the cosmological model. It means that magnetic measurements are presented a new test for exploration of cosmological models and for determination of the basic parameters of dark matter and dark energy.

Table 3: Magnetic field strengths for a number of GPS sources in various cosmological models (with different deceleration parameters).

Object		$q_0 = 0$	$q_0 = 0.5$	WDE = -1	WDE = -1 + 2z
1840+3900	$B(l_0/l)^4$(G)	0.0015	0.0195	0.0035	0.0286
	B/B_0	1.000	13.120	2.381	19.184
0646+4451	$B(l_0/l)^4$(G)	0.0006	0.0095	0.0016	0.0158
	B/B_0	1.000	15.758	2.740	26.342
1424+2256	$B(l_0/l)^4$(G)	0.0000	0.0005	0.0001	0.0009
	B/B_0	1.000	18.023	3.113	32.993
1616+0459	$B(l_0/l)^4$(G)	0.0000	0.0004	0.0001	0.0006
	B/B_0	1.000	13.974	2.463	21.427
1645+6330	$B(l_0/l)^4$(G)	0.0186	0.1521	0.0299	0.1534
	B/B_0	1.000	8.163	1.603	8.235
1850+2825	$B(l_0/l)^4$(G)	0.0003	0.0029	0.0006	0.0033
	B/B_0	1.000	9.255	1.777	10.537

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Figures captions

(See files: fig1.eps, fig2.eps, fig3.eps, fig4.eps, fig5.eps, fig6.eps, fig7.eps.)

Fig.1. Structure of the AGN nearest region: accretion disk, corona and outflow wind lines.

Fig.2. The results of polarization measurements of the sample chosen by Cabanac et al., 2005.

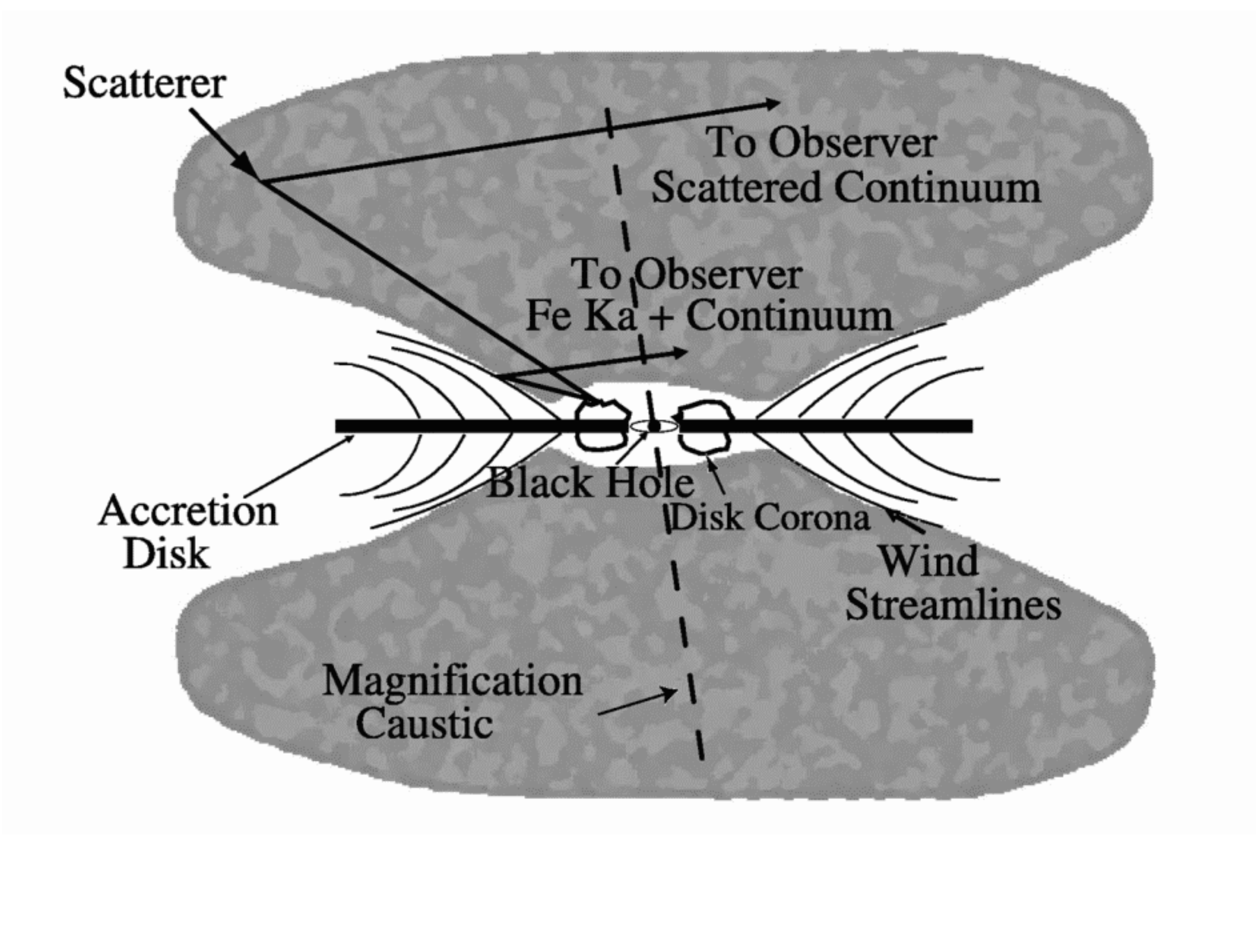
Fig.3. The confidence level of electric vectors alignment for QSOs (from Cabanac et al.,2005).

Fig.4. Mechanism of production of polarized radiation in the spherically symmetric scattering envelope with a dipole magnetic field.

Fig.5. Dependence of the polarization of radiation from the optically thick disk on the angle between the line of sight and the normal to the disk.

Fig.6. Spectrum of polarized radiation scattered in the outflow from a rotating supermassive black hole. The magnetic field is suggested Parker-type structure.

Fig.7. Results of calculation of polarization of radiation scattered in the spherical outflow with a dipole magnetic field from a supermassive black hole.



Scatterer
To Observer
Scattered Continuum
To Observer
Fe Ka + Continuum
Black Hole
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Wind
Streamlines
Magnification
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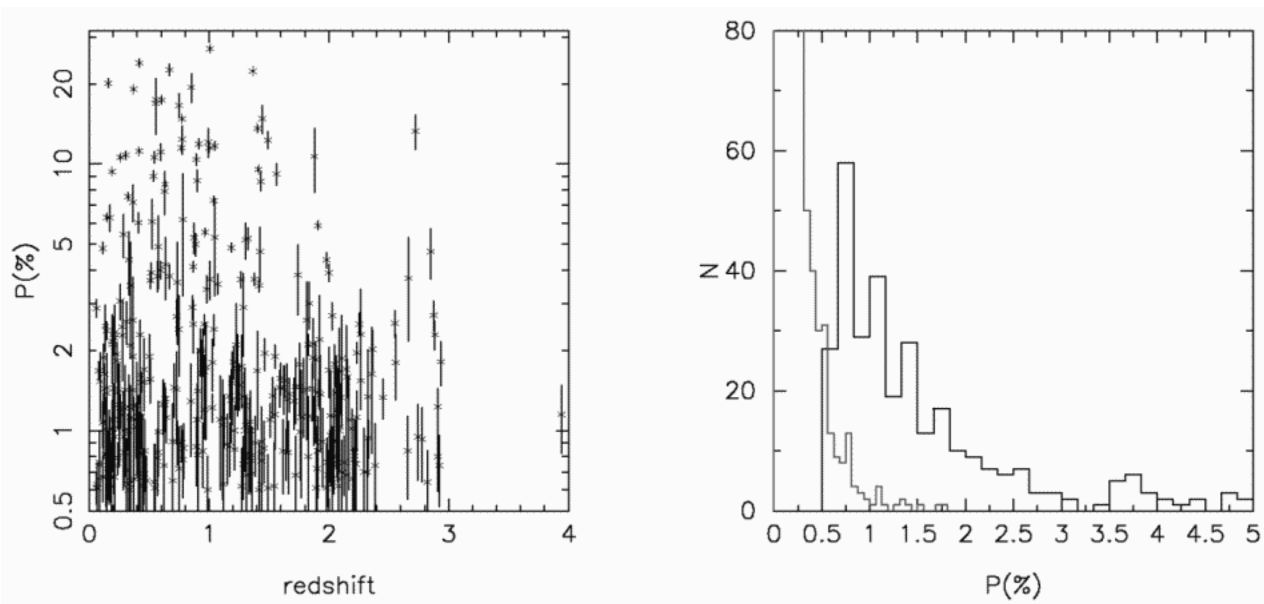
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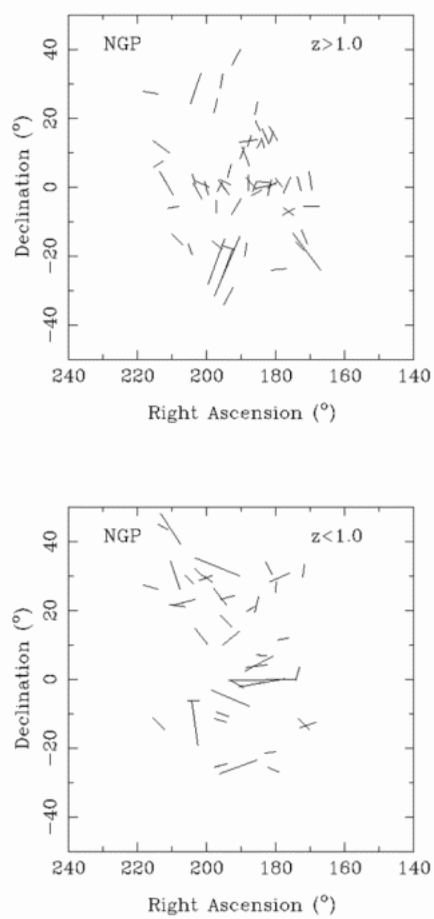
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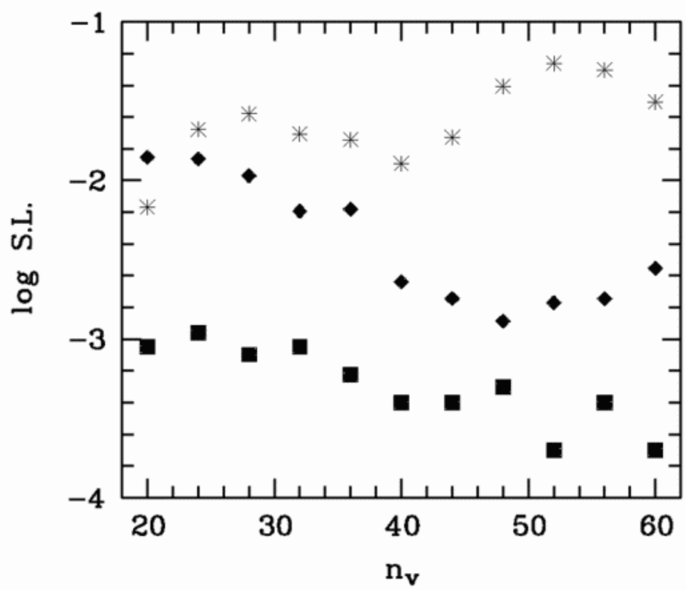
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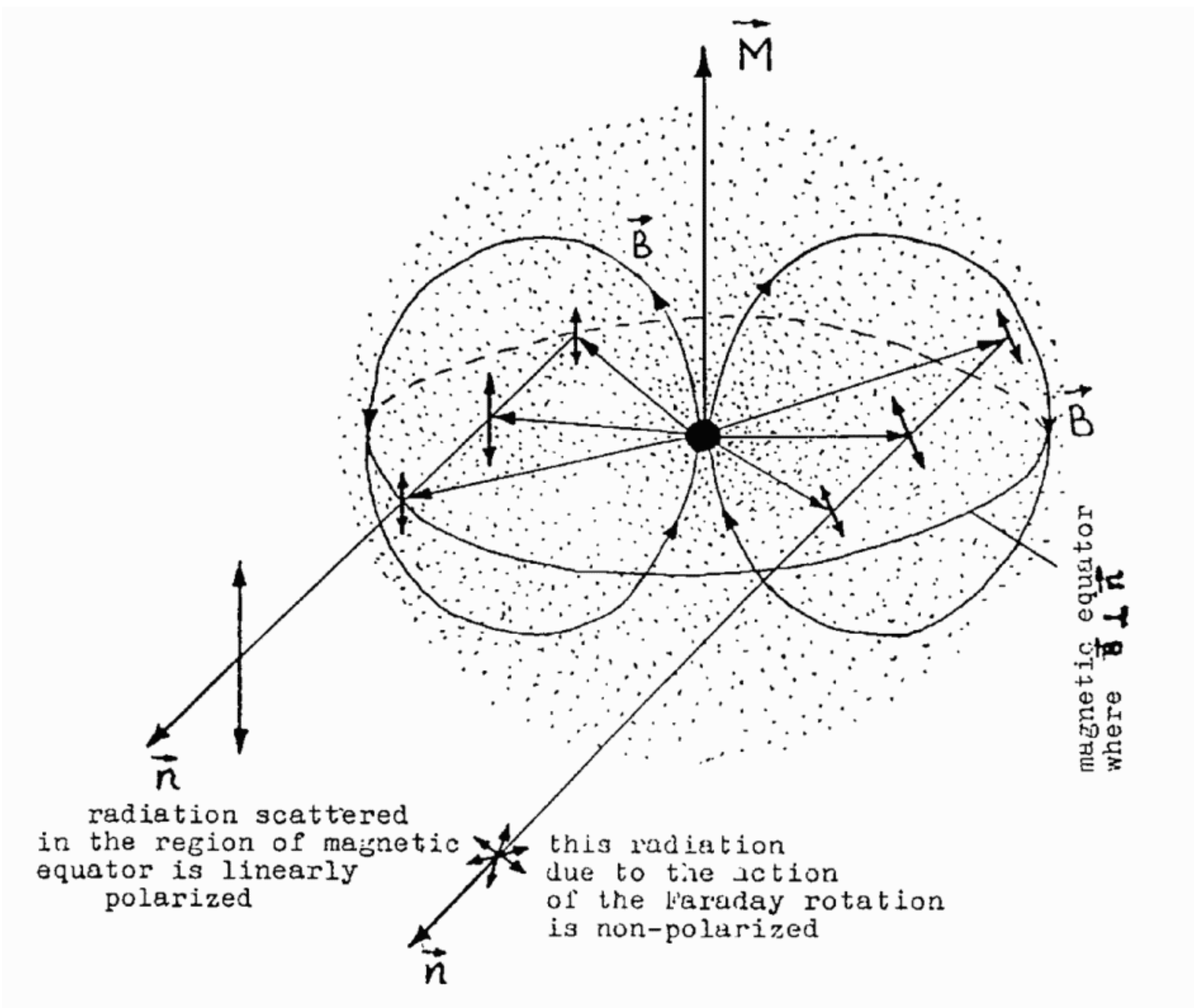
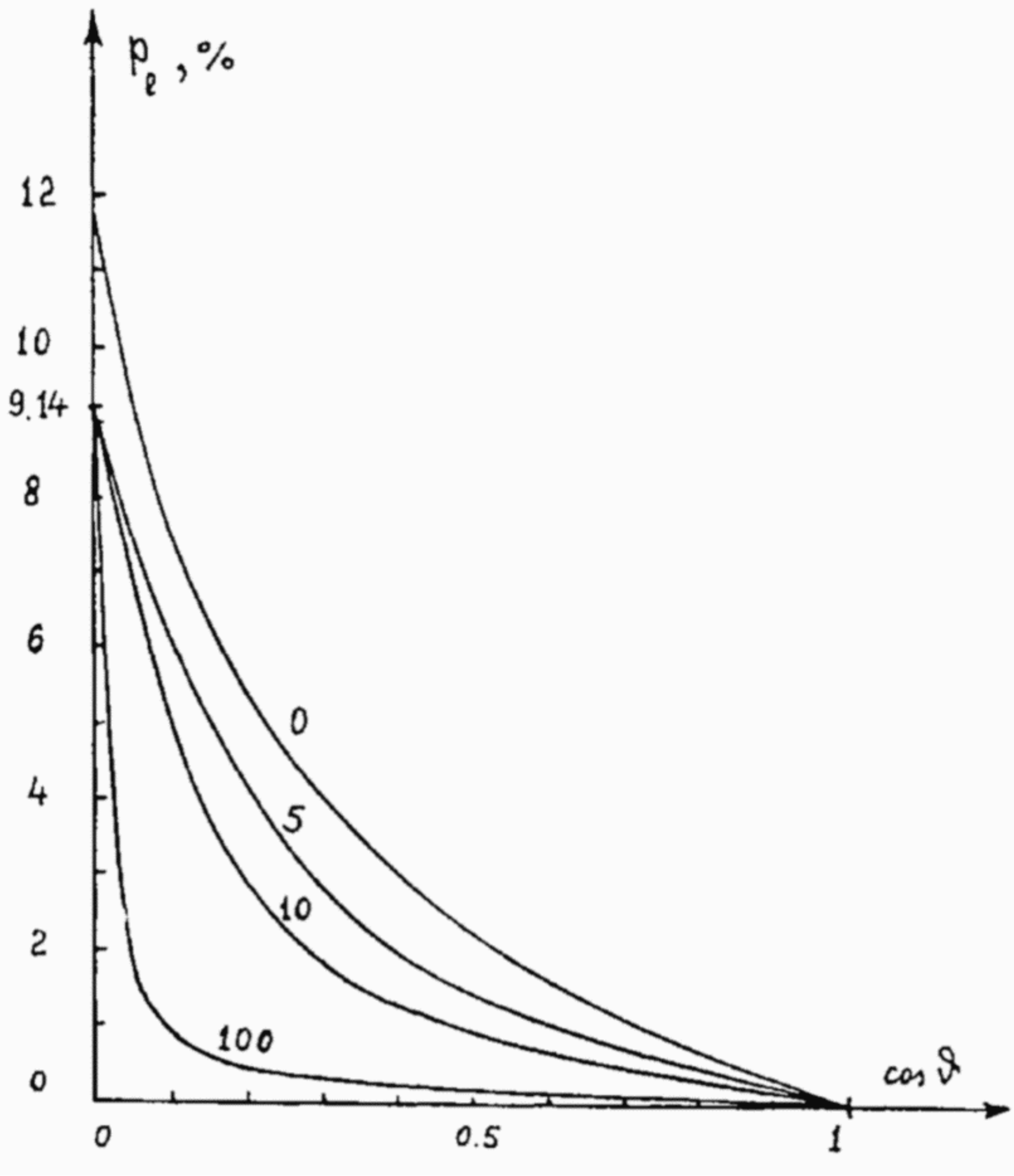
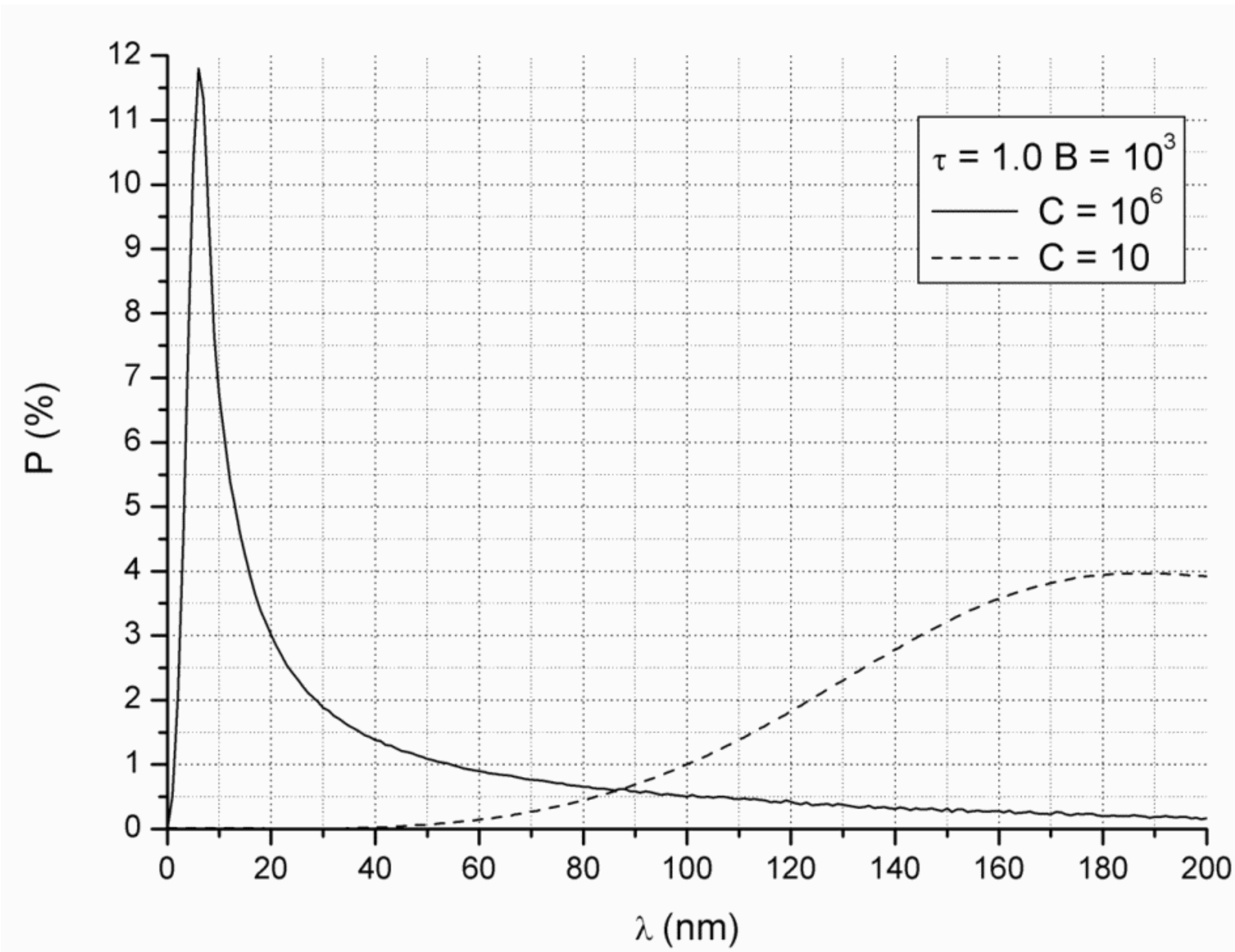


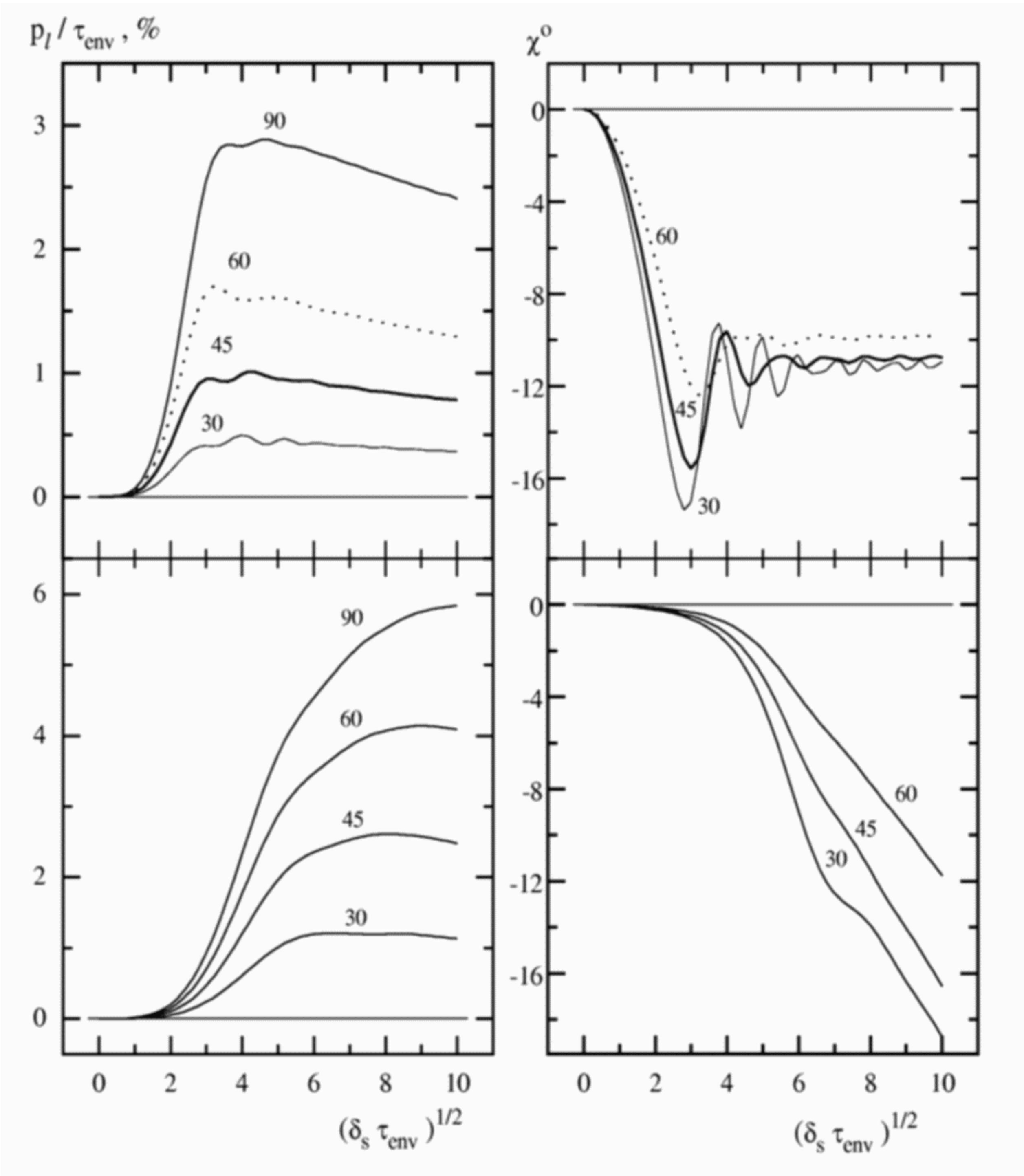
$\vec{M}$
$\vec{B}$
$\vec{B}$
magnetic equator where $\vec{B} \perp \vec{n}$
$\vec{n}$
radiation scattered in the region of magnetic equator is linearly polarized
this radiation due to the action of the Faraday rotation is non-polarized
$\vec{n}$



p_ℓ , %
12
10
9.14
8
6
4
2
0
0
5
10
100
cos ϑ
0
0.5
1



τ = 1.0 B = 10^3
C = 10^6
C = 10
P (%)
λ (nm)
0
1
2
3
4
5
6
7
8
9
10
11
12
0
20
40
60
80
100
120
140
160
180
200



p_l / τ_{env} , %
χ^o
90
60
45
30
0
1
2
3
4
6
-4
-8
-12
-16
10
8
$(\delta_s \tau_{env})^{1/2}$
$(\delta_s \tau_{env})^{1/2}$